

## **LIDAR Studies of Small-Scale Lateral Dispersion in the Ocean**

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### **LONG-TERM GOALS**

Our long-term goal is to better understand lateral mixing processes in the ocean on scales of 10 m to 10 km, i.e., the “submesoscale”. We aim to understand the underlying mechanisms and forcing, as well as the temporal, spatial, and scale variability of such mixing. This research will contribute to fundamental knowledge of ocean dynamics at these scales, and to efforts to properly parameterize sub-grid scale mixing and stirring in numerical models. Ultimately our research will also enhance modeling and understanding of upper ocean ecosystems, since the flow of nutrients and plankton depends on stirring and mixing at these scales.

Note: This report has overlaps with those by Miles Sundermeyer, Brian Concannon, and Eric Skylinstad, since we have done the field work and its analysis together.

### **OBJECTIVES**

One objective of our work is to determine the extent to which shear dispersion – the interaction of vertical mixing with vertical shear – can explain lateral dispersion at scales of 10 m to 10 km. A second objective is to determine whether slow but persistent vortices enhance the stirring attributable to shear dispersion. We also share the overall objectives of the Lateral Mixing DRI to try to determine the extent to which submesoscale stirring is driven by a cascade of energy down (in wavelength) from the mesoscale versus a propagation of energy upwards from small mixing events (e.g., via generation of vortices). A key technical goal of our work is to develop the use of airborne LIDAR surveys of evolving dye experiments as a tool for studying submesoscale lateral dispersion.

This annual report comes near the end of year 5 of a 5 year study as part of the “Scalable Lateral Mixing and Coherent Turbulence” (a.k.a., LatMix) DRI. The main effort of the present work is a collaboration between J. Ledwell and E. Terray (WHOI), M. Sundermeyer (UMass Dartmouth), B.

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Concannon (NAVAIR), and Eric Skillingstad, Murray Levine, Steve Pierce, and Brandy Kuebel Cervantes at OSU. This project was also performed jointly with a collaborative NSF grant to J. Ledwell, E. Terray, and M. Sundermeyer (see “Related Projects” below), although the term of that grant has ended. ONR support for this work included the airborne LIDAR operations as well as a substantial part of the field operations and analysis.

## **APPROACH**

Our approach is to release dye patches on an isopycnal surface in the seasonal pycnocline, and along the Gulf Stream front, and to survey their evolution for periods of 1 to 6 days, in collaboration with other investigators in the DRI. Two major field experiments have been conducted under the LatMix DRI, one 21 day experiment in the Sargasso Sea in June 2011, and one 25 day experiment along the North Wall of the Gulf Stream in Feb/Mar 2012. Both efforts were multi-ship, multi-investigator efforts, of which the dye, drifter, and LIDAR work (in 2011 only) under this project were one part. Ongoing analysis of data from these field efforts is a collaborative effort between the field PIs, numerical modelers, and theoreticians.

## **WORK COMPLETED**

A data analysis meeting for the LatMix DRI was held at Stanford University in January, 2013, hosted by Lief Thomas, and chaired by Ledwell. The main objectives of this meeting were to share results from both the 2011 and 2012 field efforts, and to enhance collaborations across facets of field experiments, theory and numerical modeling. Ledwell also helped organize and chaired a meeting of LatMix PIs the evening before the all day review meeting of LatMix in Chicago, on 17 September 2013. Although Ledwell’s lab supported the dye releases in the 2012 experiment, most of Ledwell and Terray’s efforts in the past year have been directed at analysis of the 2011 experiment. In particular we have focused on the following:

- 1) Analysis and interpretation of the 2011 drifter and CTD/dye sampling data collected from towed instruments (UMASS and OSU) together with ADCP, sea surface temperature, and sea surface salinity data from underway instruments. This is work done with Birch, Sundermeyer, Levine, Pierce, Keubel Cervantes, with contributions from D’Asaro and Kunze.
- 2) Processing and analysis of the 2011 LIDAR data set, with emphasis on plan view maps of the LIDAE return as well as inversion of the fluorescein dye signal to obtain estimates of 3-D fields. This work has been done with Concannon and Sundermeyer, with contributions from Levine and his group, and from Skillingstad and D’Asaro.

Ledwell also chaired a meeting of LatMix PI’s in Chicago on the evening before the all-day ONR review meeting of LatMix on 17 September 2013, and he presented the kick-off overview talk for that review meeting.

## **RESULTS**

A total of nine dye release experiments were conducted during the June 2011 field effort, two 6-day rhodamine experiments, and seven 26-36 hr fluorescein experiments. The two main rhodamine experiments served to provide a view of the larger-scale (1-10 km, up to as much as 80 km) characteristics of the mixing and strain environment. Meanwhile, the smaller and shorter lived fluorescein experiments provided snapshots of the small-scale variability and early evolution of the dye

dispersal. Approximately daily surveys of the two rhodamine experiments were conducted during the 6 days in which they were tracked. Summary maps of the dye patches for the second of the two main rhodamine experiments are shown in Fig. 1. The diapycnal diffusivity was found to be between  $2 \times 10^{-6}$  and  $5 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$  for both experiments from the time series of the mean vertical profiles (Fig. 2). These estimates provide a benchmark with which to compare estimates based on microstructure and fine structure measurements of other LatMix PIs, particularly L. Goodman, T. Sanford and R.-C. Lien, and with the dye-based estimate from the Lagrangian float of E. D'Asaro. Elongation of the tracer patch, in the zonal direction for the first experiment, and roughly meridionally for the second, revealed confluence rates of order  $6 \times 10^{-6} \text{ s}^{-1}$  and up to  $4 \times 10^{-5} \text{ s}^{-1}$  for the first and second experiments, respectively. These values agreed roughly with estimates derived from the drogued drifters released with the dye. Allowing for the effects of strain elongating the patch in one direction, and narrowing it in the other, we infer lateral diffusivities from dye distributions of  $0.5 \text{ m}^2 \text{ s}^{-1}$  to  $4 \text{ m}^2 \text{ s}^{-1}$ .

A major result from the dye analysis to date is that bulk dispersion estimates derived from the two main rhodamine experiments were found to be larger than could be explained by shear dispersion. Specifically, an analytical model that incorporates time dependent lateral strain, vertical shear measured with hull-mounted ADCP, and a fixed diapycnal diffusivity equal to that derived from the observed dye patches, was integrated in time to obtain a best fit to parameters observed in the field observations (Fig. 3). Results of the model showed that neither low frequency or steady shears, nor near-inertial or higher frequency shears observed during the experiments, together with the observed diapycnal mixing, could explain the observed lateral spreading of the tracer patches. Dan Birch, who started work on LatMix as a UMass post-doc, has led this analysis. He has drafted a manuscript, working on it during the summer of 2013 as a Visiting Investigator at WHOI during a break from his new job as a high school physics teacher, which he started in September 2012. We expect to submit this manuscript by the end of 2013.

The fluorescein dye patches, typically tracked for 24 to 36 hrs, were surveyed by airborne LIDAR, led by Brian Concannon, as well as by in situ instruments from UMass Dartmouth and OSU. M. Levine's group is leading the analysis of the fluorescein in situ data, while M. Sundermeyer is leading the analysis of the airborne LIDAR data, in collaboration with Concannon, and Ledwell and Terray. Analysis of the LIDAR data, including improved inversion approaches and in situ calibration to obtain absolute dye concentration, are still ongoing. However, preliminary maps of the dye concentrations by the LIDAR reveal a rich structure in the dye patches, even early (less than 8 hrs) into the experiments. Results from one of the fluorescein experiments are shown in Fig. 4. The plan views in that figure are from a series of passes of the aircraft over the dye patch. The depth-distance section was obtained from a preliminary inversion of the dye signal using the methods described in Terray and Sundermeyer (2005), and Sundermeyer et al. (2007).

Finally, a surface release of dye, done as an add-on to one of the releases in the seasonal pycnocline, yielded a view of the birth of banded structures in the mixed layer with a large aspect ratio (Fig. 5), and also showed subduction of dye into the top of the pycnocline. A numerical LES model by Eric skyllingstad of OSU has replicated these structures and show that they occur in the absence of Stokes drift associated with wind waves, though they do result from wind stress, and their scale depends on the lateral density gradient within the mixed layer.

To summarize the main results, which we can only assert apply to summertime conditions in the seasonal pycnocline in the subtropics:

1. Isopycnal diffusivity is of order  $1 \text{ m}^2/\text{s}$  at scales of 1 to 10 km.
2. Diapycnal diffusivity is on the order of  $5 \times 10^{-6} \text{ m}^2/\text{s}$  or less.
3. The observed isopycnal diffusivity at scales of 1 to 10 km cannot be explained by shear dispersion.
4. LIDAR has proven to be an effective means of surveying dye patches, at least within six hours of release.
5. Intriguing roll structures evolve in the mixed layer on time scales of an hour in the presence of a lateral density gradient and wind. LES simulations reproduce these structure without the benefit of wave-induced Stokes drift.

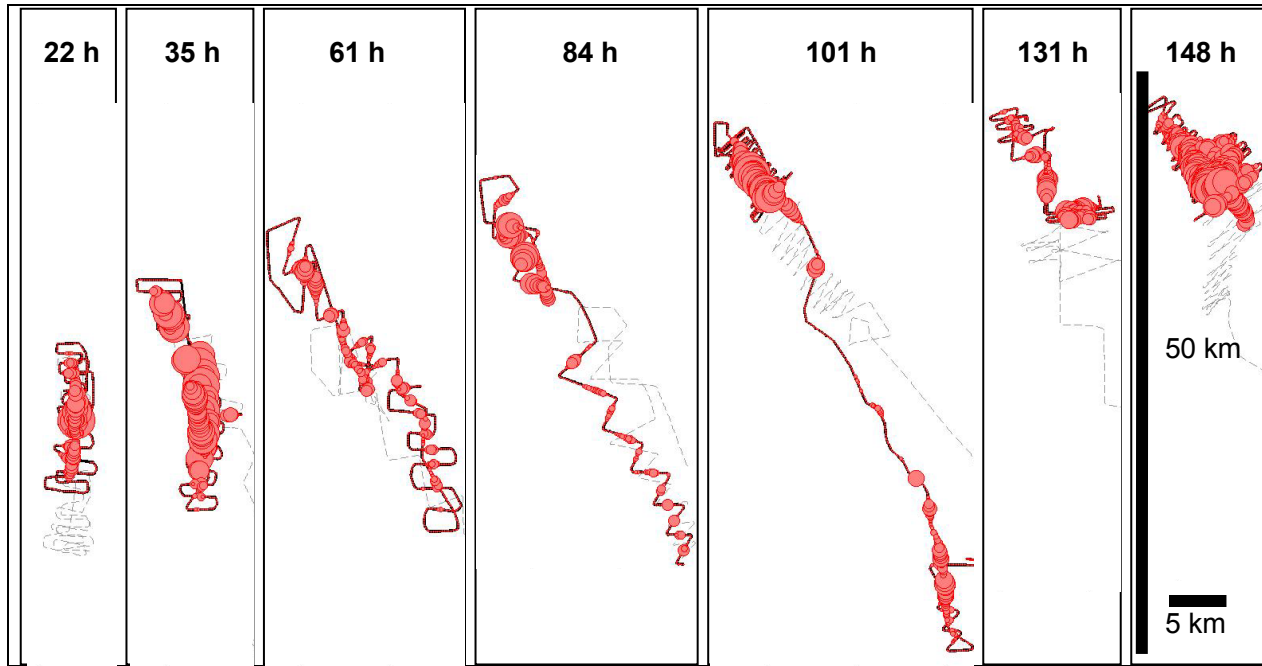
## **IMPACT/APPLICATIONS**

Our research will contribute to fundamental knowledge of ocean dynamics at the “submesoscale”, and to efforts to properly parameterize sub-grid scale mixing and stirring in numerical models. Ultimately our research will also enhance modeling and understanding of upper ocean ecosystems, since the flow of nutrients and plankton depends on stirring and mixing at these scales.

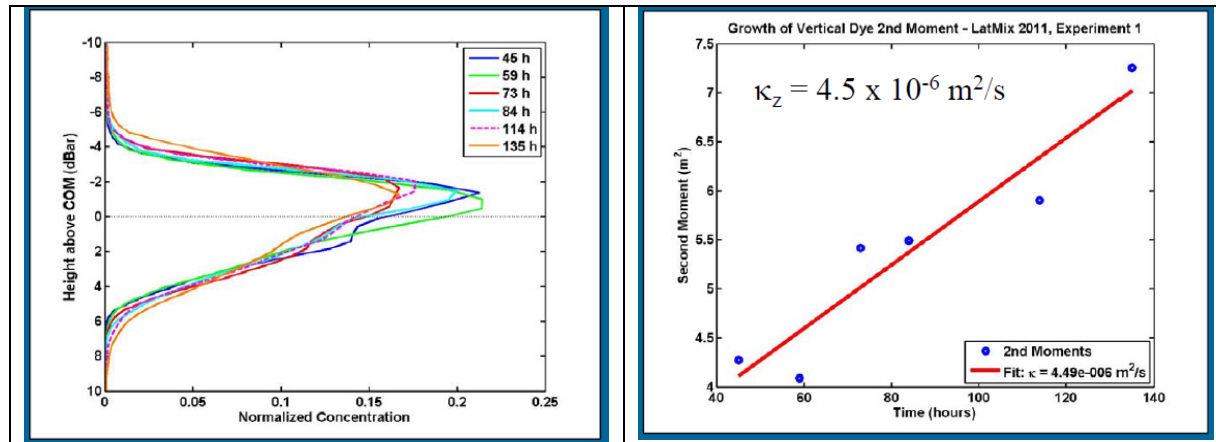
## **RELATED PROJECTS**

The above work and findings represent a joint effort on the part of LatMix DRI PIs Ledwell and Terray (WHOI) and Sundermeyer (UMass Dartmouth) under ONR grants N00014-09-1-0175 and N00014-09-1-0194, respectively, Brian Concannon (NAVAIR) under ONR award N0001411WX21010, Murray Levine and his group, and Eric Skyllingstad. Furthermore, our work is coordinated with all the other projects within the Lateral Mixing DRI.

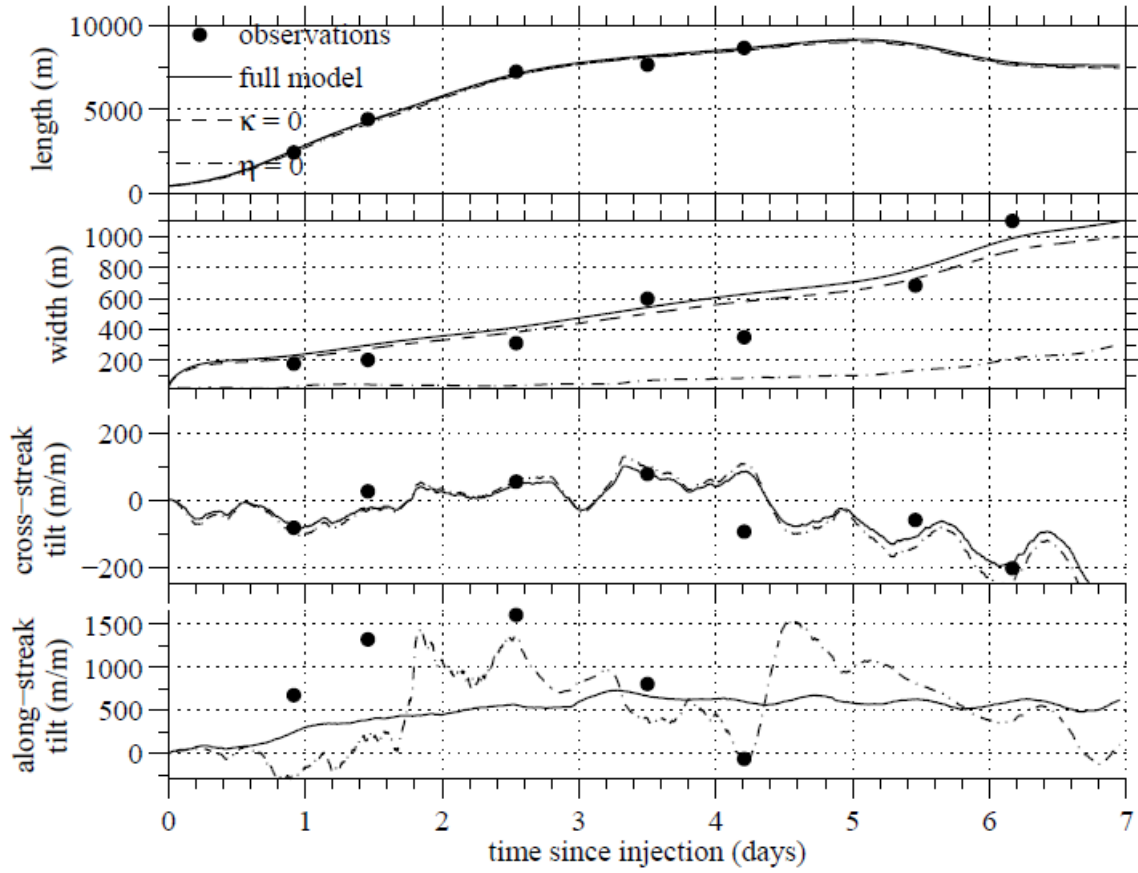
Field instrumentation used in the 2011 field work was purchased in part under DURIP grant N00014-09-1-0825, and in part under a related NSF project entitled “Collaborative Research: LIDAR Studies of Lateral Dispersion in the Seasonal Pycnocline”, NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI). The PIs efforts under the ONR LatMix DRI are being performed in coordination with the PIs efforts under the above mentioned NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI).



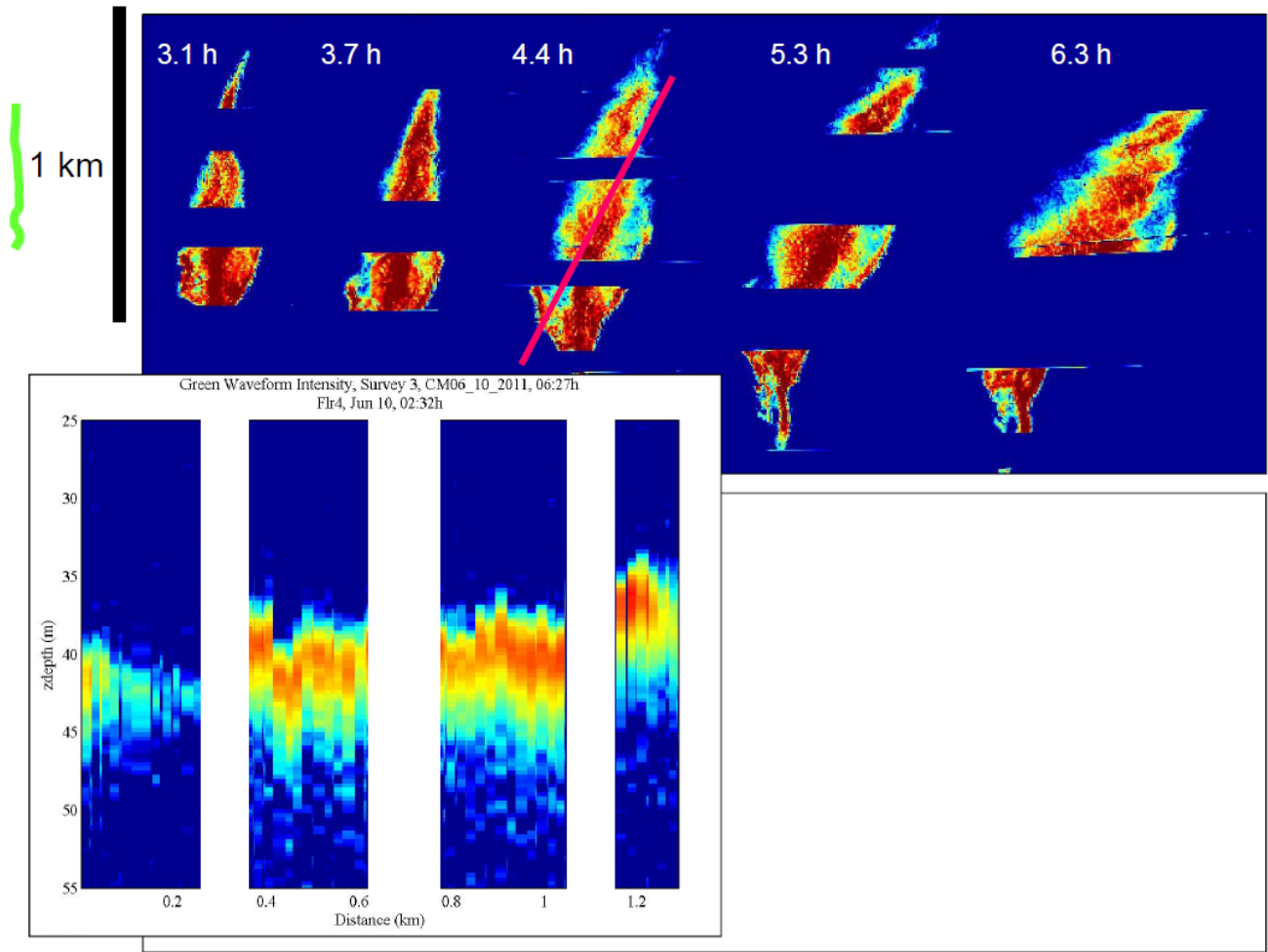
**Fig. 1.** Plan views of the second 2012 rhodamine dye experiment as surveyed using the UMass Acrobat tow package over the approximately 150 hrs following release. Successive maps show the elongation and spreading of the tracer patch from its initial release of approximately 1.5 km long x 100 m wide to more than 50 km long and 5 km wide.



**Fig. 2.** Left panel: A series of mean vertical profiles from surveys centered at various times between 45 hours and 135 hours since the release of a streak of dye on 10 June 2011. Right panel: the second moments of the profiles as a function of time. The slope of the line through these second moments gives a diapycnal diffusivity of  $4.5 \times 10^{-6} \text{ m}^2/\text{s}$ .

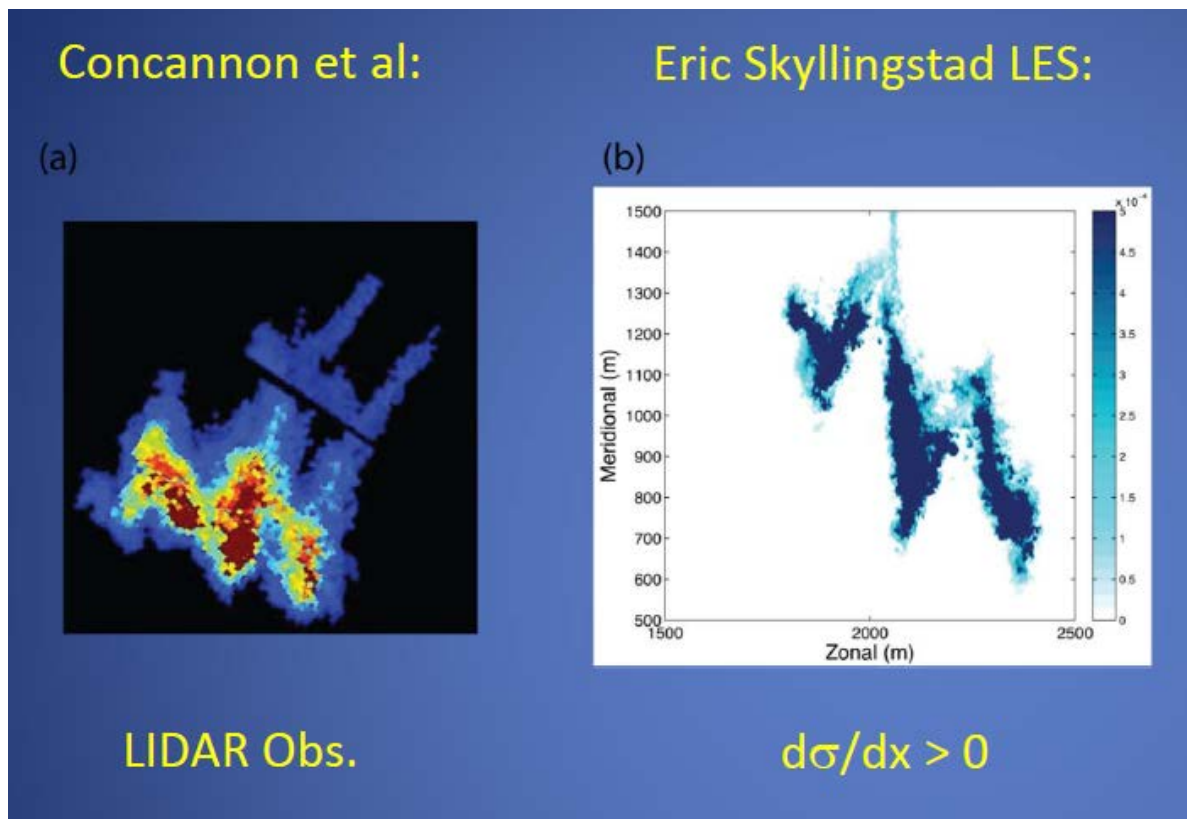


**Fig. 3.** The length, width, cross-streak tilt, and along-streak tilt of the second Rhodamine patch released in 2011 as a function of time. The dots show the observations. A full model developed by D. Birch, which uses the measured diapycnal diffusivity, observed shear estimated from the ship's ADCP, and the confluence estimated from the drogues, fits the evolution of the width well only if an along-isopycnal diffusivity,  $\eta$ , beyond that due to shear, of order  $1 \text{ m}^2/\text{s}$  is included in the model, to give the dashed line in the second panel as opposed to the dot-dashed line for  $\eta = 0$ .



**Fig. 4. Upper Panel: Plan views of a fluorescein path released in the pycnocline obtained between 3 and 6 hours after release by airborne LIDAR. Lower panel: A depth-distance section from the track shown along the 4.4-hour plan view obtained from a preliminary inversion of the LIDAR profiles. The green track in the upper left shows the track along which the dye was initially released. This and the plan views have been offset from one another along the horizontal axis for clarity.**





**Fig. 5.** Left panel: plan view of fluorescein in the mixed layer approximately one hour after release of a small patch of dye. Right panel: LES simulation of a dye patch released in a numerical model by E. Skillingstad under the same wind and hydrographic conditions as for the observations. The scales in the two panels are similar.

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